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Experimental investigation of the sound transmission of vegetated roofs

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ABSTRACT

The purpose of this research was to determine the phenomenological parameters that impact the sound transmission of vegetated roofs. A reverse indoor-to-outdoor testing method involving propagating sound from an interior diffuse field to an exterior free field was first implemented at an existing field site. The findings from the field work supported the development of a purpose-built field laboratory specifically designed and commissioned as part of this research. Transmission loss measurements were completed on 2 non-vegetated reference panels, on gradients of substrate depth (25-mm increments), and on 2 plant communities established in 150 mm of substrate depth. Increased transmission loss, resulting from the installation of vegetated roof material layers on the reference roof, at the field site (wood frame construction) and at the field laboratory (light-weight metal) generally aligned in the low and mid frequency ranges. The increased transmission loss of the wood frame roof was 5–13 dB in the 50–2000 Hz frequency range, and up to 8 dB above 2000 Hz. For the light-weight metal deck, the increased transmission loss was up to 10 dB, 20 dB, and >20 dB in the low, mid, and high frequency ranges, respectively. Field mass law, using an effective mass to describe the composite roof deck, predicted the transmission loss of non-vegetated reference roofs. A gradient increase in substrate depth (equated in terms of mass) incrementally increased transmission loss, but not as predicted by mass law. A variation in the moisture content of the substrate did not translate to a measurable change in transmission loss. The deep roots of the coastal meadow community contributed to an increase in transmission loss relative to the shallow-rooted sedums community. The results of this research confirm that vegetated roofs increase transmission loss over non-vegetated roofs and have a beneficial application towards architectural situations requiring high transmission loss and specifically mitigation of low frequency noise.

1. Introduction

The focus of sound transmission research on building envelopes most commonly emphasizes the transmission of airborne noise from the urban environment into the habitable areas of buildings. A vegetated roof is a constructed boundary between the natural exterior and indoor environments. The benefits of vegetated roofs may be the most significant to habitable spaces in urban development below aircraft flight paths and transit corridors. Noise generated in industrial or infrastructure facilities transmitting sound to the outside is also a concern. When excessive noise is generated within a building (e.g., from a district water pumping station), a vegetated roof may provide a community benefit through the reduction of excessive external noise. The greatest benefits will likely be recognized in the case of lightweight roof assemblies (which normally have a low sound insulation) and/or open plenum ceilings used in multi-family residential, industrial, commercial, and institutional development.

The acoustical characteristics of vegetated roofs affect not only the absorption and reflection of sounds from the roof but also the transmission of sound into and out of the building. The material attributes of vegetated roofs determine the degree of sound transmission and absorption over the full range of acoustical frequencies considered in planning and landscape/architecture, with the substrate and vegetation being the two components expected to have the most significant effects. An investigation of the sound absorption of vegetated roofs is reported elsewhere (unpublished results; submitted to JASA for publication); this paper deals with sound transmission only.

Single-material panels and complex building envelopes, such as vegetated roofs, introduce large changes of acoustic impedance into the transmission path of propagating sound. The transmission loss of vegetated roofs may be modeled as a single-layer panel or a multi-layer partition. The roof deck and materials can be considered, as a first approximation, a single massive element; in

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acoustical terms, multi-layer components which are bonded together permanently across their entire surface form one solid layer to which the addition of the vegetated roof material layers and the vegetated substrate is considered an increase in mass.

The fundamental principle of single panel transmission loss theory is that sound energy incident on a solid panel imparts movement to the panel and precipitates the transmission of wave motion, of decreased intensity, into the fluid medium of air on the opposite side of the panel. The measure of how much sound energy is reduced in transmission through materials is the transmission loss (TL; in decibels [dB]), which is expressed as a function of the characteristic impedance of air ($\rho_0 c_0$), panel surface mass (m_s), frequency (f), and angle of incidence (θ). The characteristic impedance of material panels is large relative to air and the transmission loss depends mainly on the mass per unit area [1]. Within the low frequency range, transmission is controlled by mass impedance; Eq. (1) defines the fundamental mass law:

$$\mathrm{TL}(\theta) = 10\log\left[1 + \left(\frac{\omega m_s \cos\theta}{2\rho_0 c_0}\right)^2\right] \quad (1)$$

A coincidence effect occurs, which reduces transmission loss at or above a critical frequency. At higher frequencies the panel impedance is a composite of mass and bending stiffness. The coincidence effect occurs when the bending wavelength in the panel matches the trace of the grazing airborne wavelength; a reduced transmission loss is maintained through damping control. Mass loading is used to the benefit of increasing transmission loss in the low frequency range and added damping is used to the benefit of reducing the coincidence effect. A literature review of empirical findings on the transmission loss of roofs highlights 3 key concepts supporting the use of vegetated roofs as acoustical barriers. First, the use of additional materials to mass-load without increasing stiffness and to add damping to the roof can virtually eliminate the coincidence effect and increase transmission loss at low frequencies. Measurements indicate that mass law may predict higher values than measured [2]. Cork overburden and other insulation materials provided significant additional transmission loss as additional surface layers on steel deck roofs in the low frequency range and eliminated the coincidence effect. A similar transmission loss trend was observed among the materials, with a generally flat transmission loss curve from 125 to 315 or 400 Hz, and material-dependent transmission loss curves with slopes varying from 18 to 30 dB per octave band [3]. Pebble overburden has been shown to increase transmission loss at low and mid frequencies [4]. Second, in the absence of vegetated roof technology, increased transmission loss can be achieved by the addition of a ceiling. This addition to the roof assembly increased transmission loss only in the mid and high frequency ranges and not in the low frequency range [1,4]. Third, sedum mats[1] provide approximately a 10-dB increase in transmission loss at low frequencies, with transmission loss increasing with frequency [5,6].

In the 1970s, due to the global increase in aircraft noise levels, novel experimental approaches to the problem of designing roof/ceiling assemblies were undertaken with the goal of increasing the transmission loss of building envelopes. The concept of a massive flexible ceiling in the floor/ceiling system was presented; "sand is an almost perfect material for sound-attenuating structures, embodying all the most desirable features-high mass, low stiffness and high damping" [7]. However, the acoustical solution was limited without an architectural solution to hold the sand in place, a concept that approximates an inversion of the material layers of vegetated roofs. As an alternative, the installation of a flexible base panel attached to the underside of the ceiling joist and the addition of 6.25–12.5 mm of sand plugging were investigated. The transmission loss prediction model was composed of the fundamental mass law term with an additional term for frequencies above 125 Hz, which generated a transmission loss slope of 18 dB/octave. This investigation occurred at the same time as the emergence of new European technologies for vegetative roof systems; however, the use of vegetated roofs as a design solution to the acoustical problems did not transpire.

Findings indicate that soil texture affects the attenuation of sound propagating through ground soils [8]. Through the investigation of outdoor sound propagation over ground, the plant root soil interface has been identified as affecting the normal specific impedance [9]. Soil conditions of moisture and compaction are variables affecting the acoustic characteristics of impedance, sound absorption, and propagation speed [10–12].

Research has validated vegetated roofs as a building envelope system with highly absorptive characteristics, and qualifies the conditions that optimize their absorption potential. Measurements of in situ vegetated roof test plots indicate that absorption is a function of substrate depth, plant community establishment, and moisture content in the plants and substrate [13].

The objective of the current research was to determine the phenomenological parameters that impact the sound transmission of vegetated roofs. A 'reverse' testing method developed in the 1970s was the genesis of the experimental setup; the test measures the transmitted acoustic intensity radiated by the roof system while the incident intensity is deduced from the average sound pressure level inside the source room below the roof [14,15]. A series of field tests were first conducted at an existing research center with a design and layout that effectively allowed the application of the test method to 2 vegetated roofs and 1 non-vegetated reference roof. The preliminary transmission loss field data led to the design and construction of a purpose-built test facility as the experimental setup. It was expected that this research would confirm that vegetating rooftops increase transmission loss, with the most significant impact in the lower frequency range. It was also expected that a frequency-dependent transmission loss would be a function of the additional mass in both the lower and higher frequency ranges, and that the increase in transmission loss would increase with frequency.

2. Methods

The vast majority of both laboratory and in situ field testing methods of transmission loss are focused on interior walls and floors, exterior building facades, and facade elements. There are no standardized test methods which have been developed specifically for the measurement of sound transmission through roofs. The ASTM (American Standard Test Method) and ISO (International Standards Organization) standards define several measurement procedures for evaluating transmission loss using sound transmission suites, a pair of reverberation rooms separated by a partition with an opening in which the test sample is mounted. The testing methods standardize a diffuse sound field generated in one room and the measurement of sound transmission through the test panel into the second room. Sound transmission suites provide a high level of control for evaluating the transmission loss of single-layer and multi-layer partition wall and floor/ceiling systems under laboratory conditions.

There are field measurement standards for transmission loss that have a source outside and not in a test room. A reverse testing method incorporating an indoor-to-outdoor procedure of propagating sound from an interior diffuse field to an exterior free field was adopted [14,16]. The method uses an intensity approach to

[1] Sedum mats are pre-grown vegetated roof systems consisting of sedum species on a mesh substrate carrier.